Results and prospects for $K \to \pi\nu\bar{\nu}$ at NA62 and KOTO

On behalf of the NA62 collaboration

Nicolas Lurkin

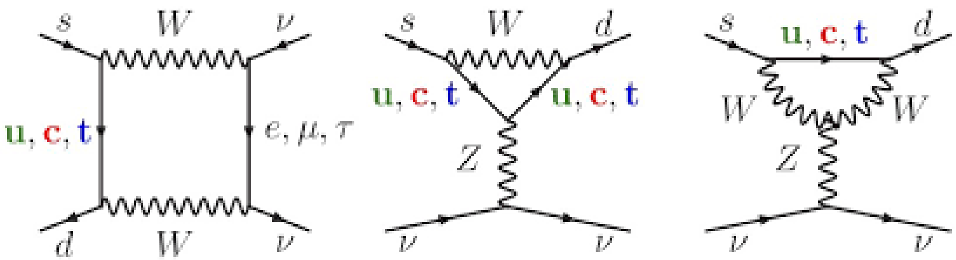
School of Physics and Astronomy, University of Birmingham

Meson 2018, 08-06-2018

Outline

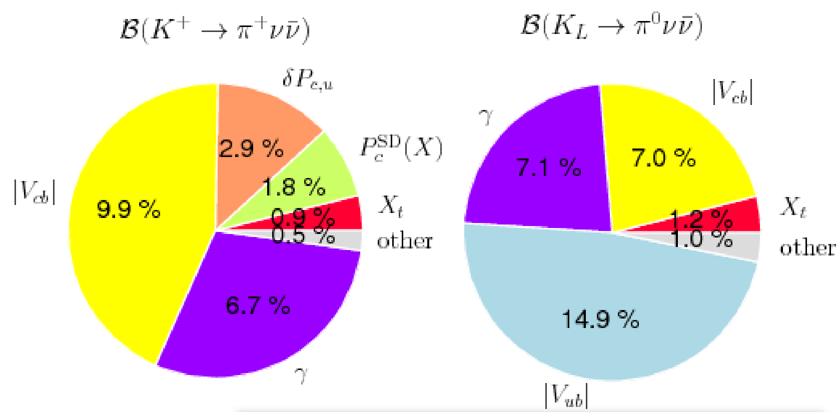
- $K \rightarrow \pi \; \nu\bar{\nu}$ in theory
- $K \rightarrow \pi \; \nu\bar{\nu}$ experimentally
- $K^+ \rightarrow \pi^+\nu\bar{\nu}$ at NA62
- $K^0 \rightarrow \pi^0\nu\bar{\nu}$ at KOTO
- $K \rightarrow \pi \; \nu\bar{\nu}$ in the future

The $K \to \pi\nu\bar{\nu}$ Process



- **Highly suppressed:**
  - FCNC process forbidden at tree level
  - CKM suppression ($s \to d$ coupling, $BR \sim |V_{ts}V_{td}|^2$)

- **Theoretically clean:**
  - Dominant short-distance contribution
  - Hadronic matrix element extracted from $BR(K^+ \to \pi^0 e^+ \nu)$
  - Theoretical error budget dominated by CKM parameters



[Buras et al., JHEP1511 (2015) 033]

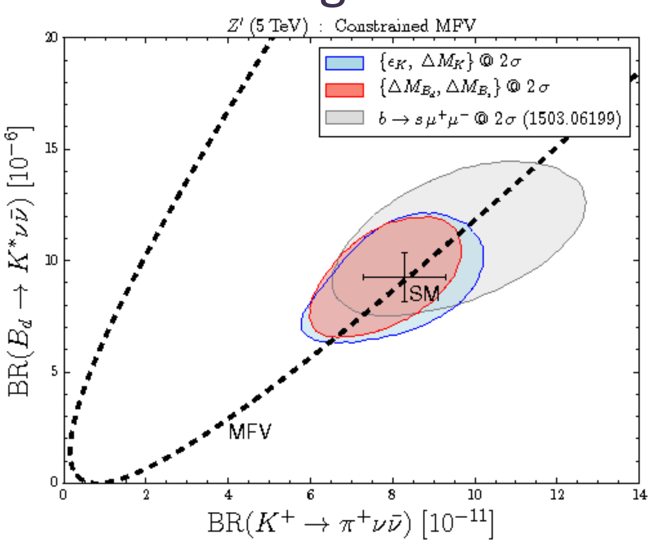
- **SM Predictions:**

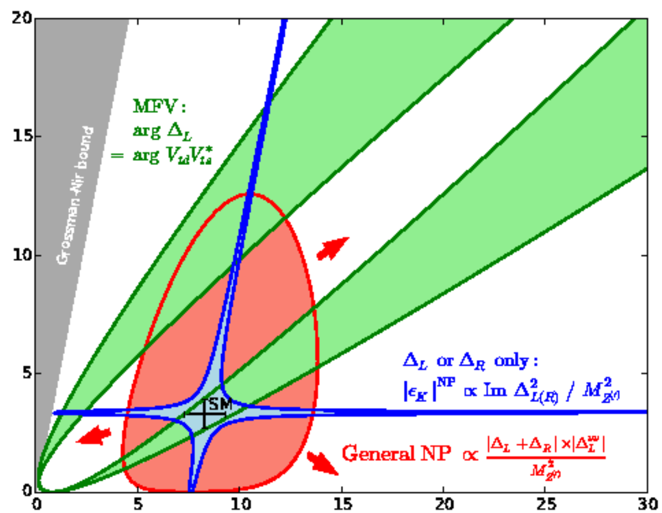
$BR(K^+ \to \pi^+\nu\bar{\nu})$	$BR(K^0 \to \pi^0\nu\bar{\nu})$
$(8.39 \pm 0.30) \times 10^{-11} \cdot \left[\frac{\lvert V_{cb}\rvert}{40.7 \times 10^{-3}}\right]^{2.8} \left[\frac{\gamma}{73.2°}\right]^{0.74}$	$(3.36 \pm 0.05) \times 10^{-11} \cdot \left[\frac{\lvert V_{ub}\rvert}{3.88 \times 10^{-3}}\right]^{2} \left[\frac{\lvert V_{cb}\rvert}{40.7 \times 10^{-3}}\right]^{2} \left[\frac{sin(\gamma)}{sin(73.2°)}\right]^{0.74}$
$(8.4 \pm 1.0) \times 10^{-11}$	$(3.4 \pm 0.6) \times 10^{-11}$

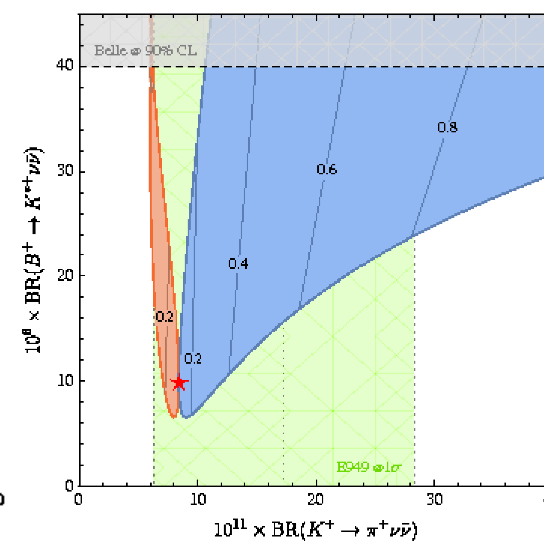
$K \to \pi\nu\bar{\nu}$ in New Physics Scenarios

- **Exploit correlation between $K^+ \to \pi^+\nu\bar{\nu}$ and $K^0 \to \pi^0\nu\bar{\nu}$**
  - Differ significantly between different classes of NP models
    - Custodial Randall-Sundrum [JHEP 0903 (2009) 108]
    - MSSM analyses [Int.J.Mod.Phys A29 (2014) no.27] [JHEP 0608 (2006) 064]
    - Simplified Z, Z' models [JHEP 1511 (2015) 166]
    - Littlest Higgs with T-parity [Eur.Phys.J. C76 (2016) 182]
    - LFU violation models [Eur.Phys.J. C77 (2017) no.9 618]

- **Combine measurement of neutral and charged channels**
  - Strong constraints on NP models





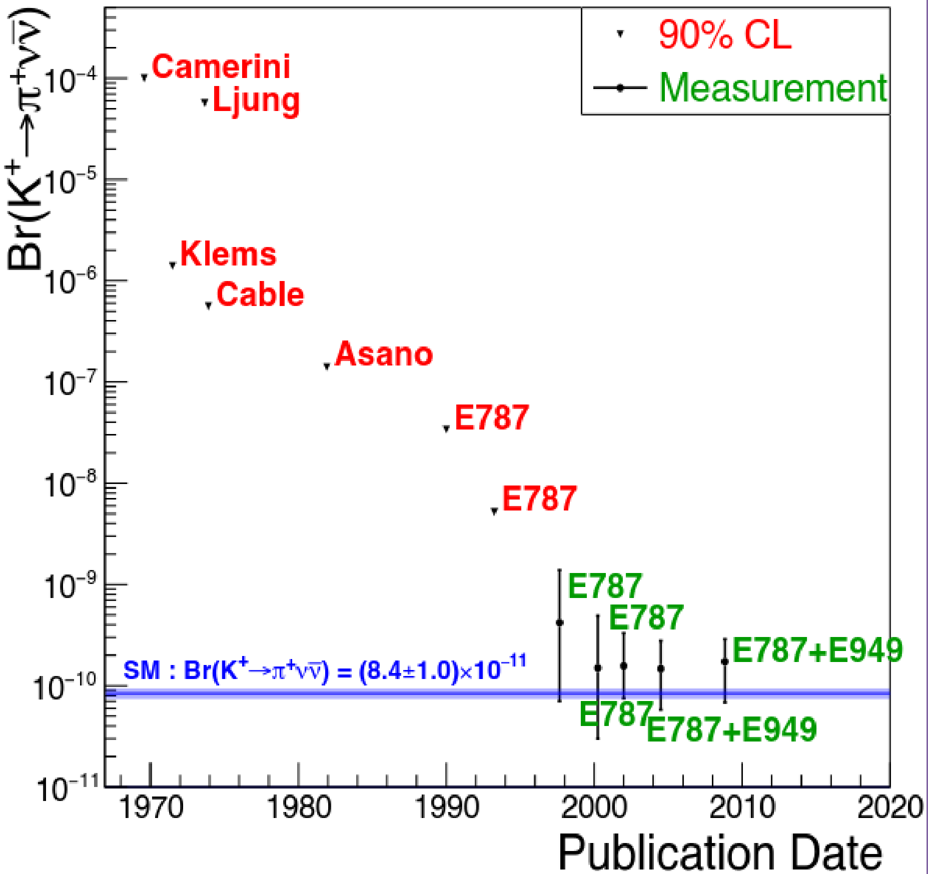


Experimental Status

[Phys. Rev. D77, 052003 (2008)]

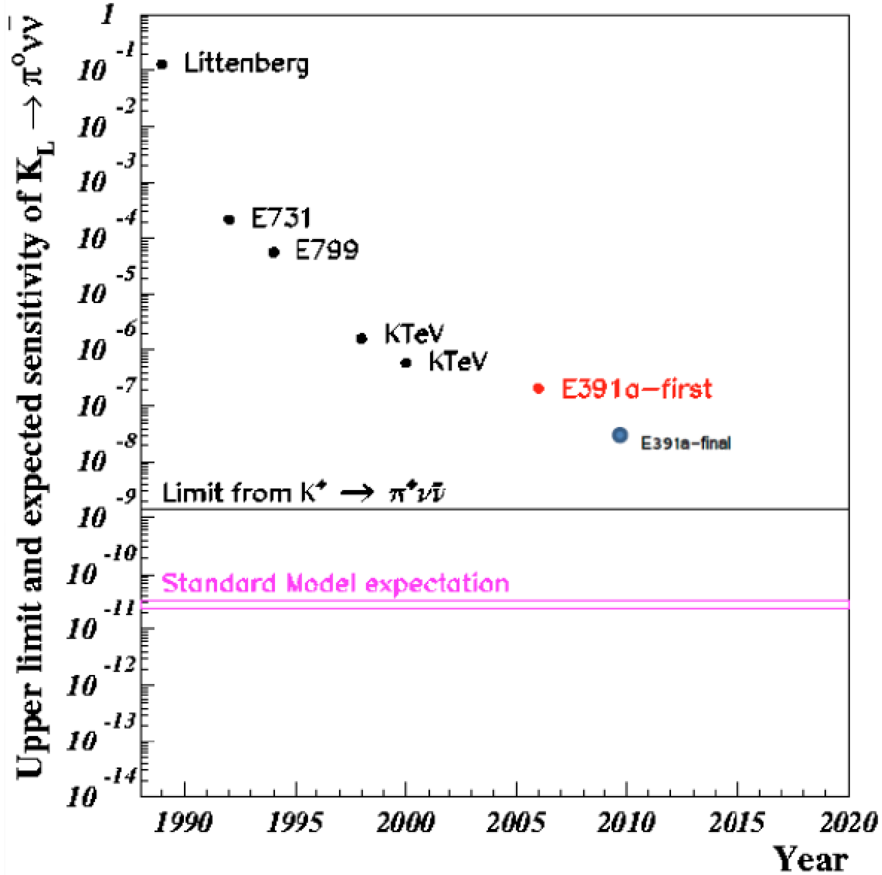
[Phys. Rev. D79, 092004 (2009)]

- $BR(K^+ \to \pi^+ \nu\bar{\nu}) = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$



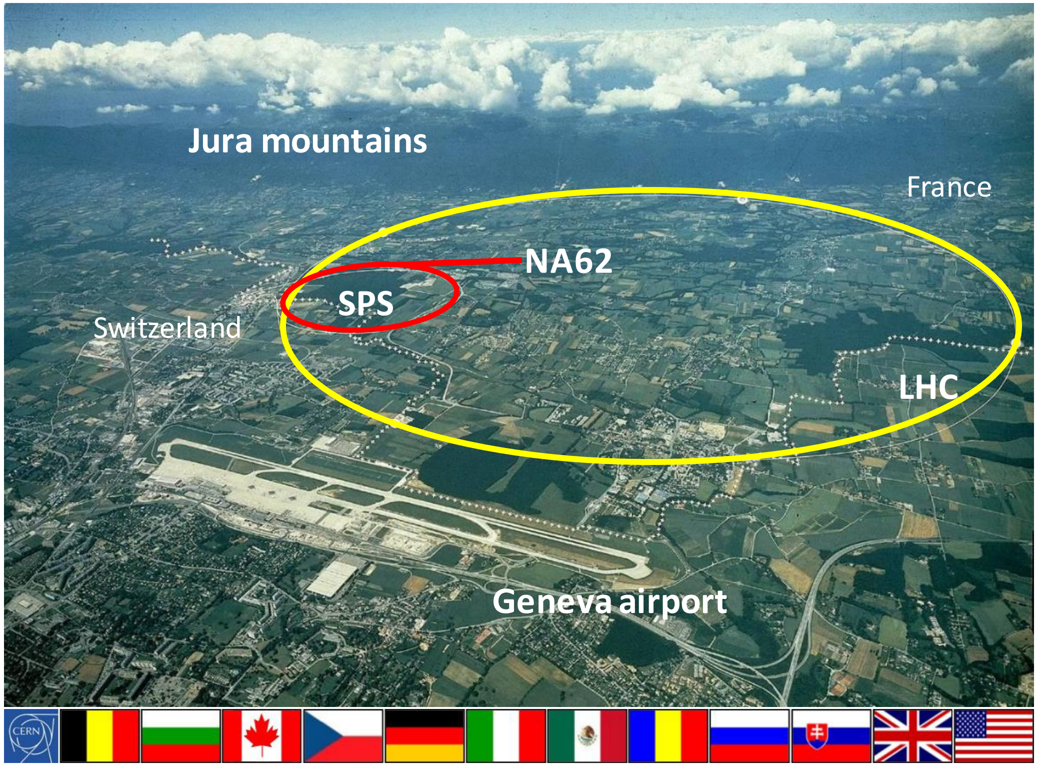
[Phys. Rev. D81, 072004 (2010)]

- $BR(K_L \to \pi^0 \nu\bar{\nu}) < 2.6 \times 10^{-8}$ (90% C.L.)



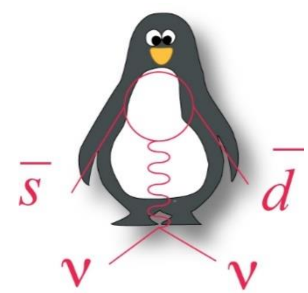
The NA62 Experiment

Fixed target Kaon experiment at CERN SPS

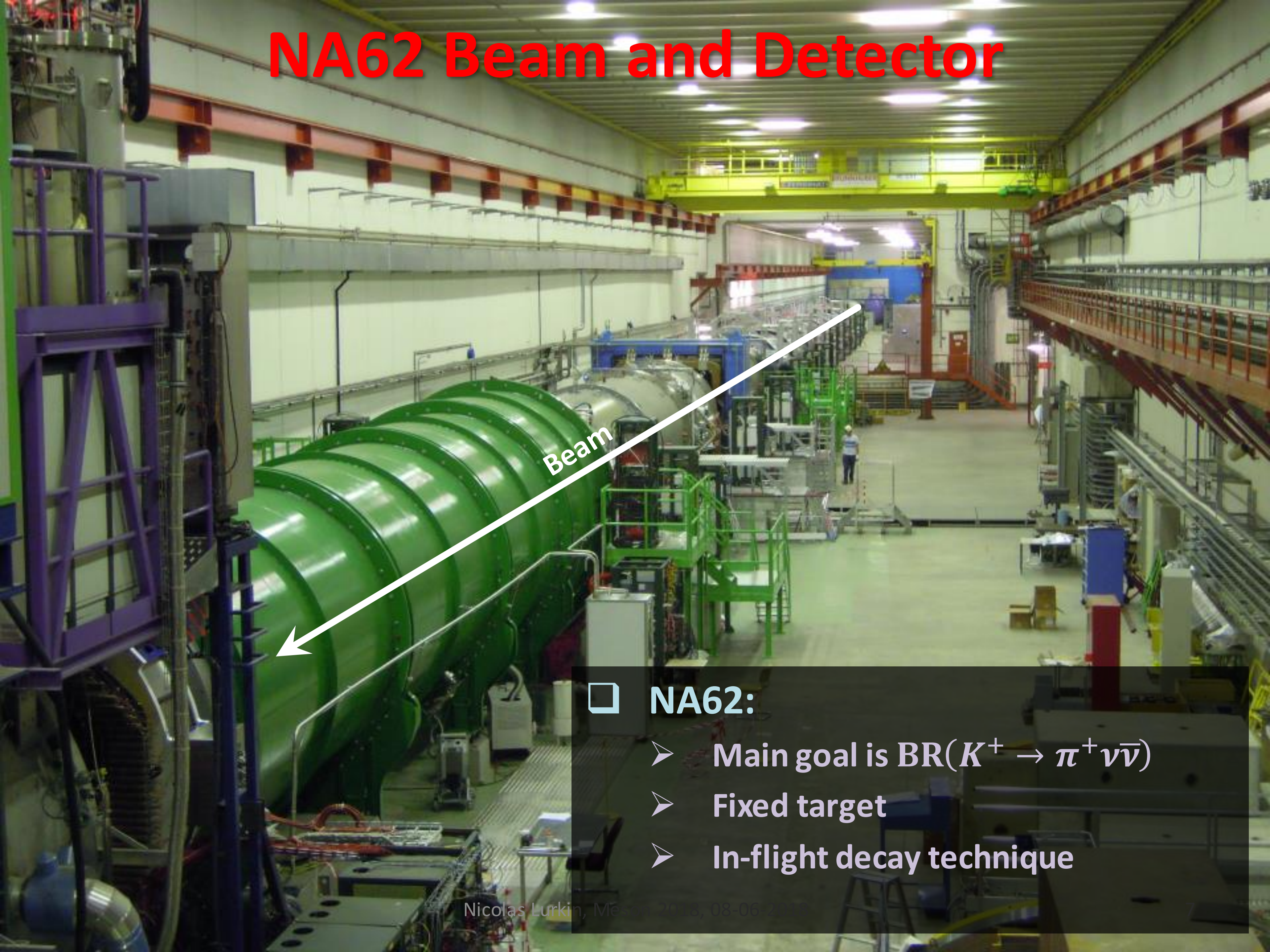


~200 participants: Birmingham, Bratislava, Bristol, Bucharest, CERN, Dubna, GMU-Fairfax, Ferrara, Firenze, Frascati, Glasgow, Lancaster, Liverpool, Louvain-La-Neuve, Mainz, Moscow, Napoli, Perugia, Pisa, Prague, Protvino, Roma I, Roma II, San Luis Potosi, Sofia, Torino, TRIUMF, Vancouver UBC

- **2008** — NA62 Approval
- **2009-2014** — Detector R&D and Installation
- **2014** — Pilot Run
- **2015** — Commissioning run
- **2016-2018** — Physics runs
- **2021-2023** — Future runs?



NA62 Beam and Detector



- **NA62:**
  - Main goal is $\mathrm{BR}(K^+ \to \pi^+ \nu\bar{\nu})$
  - Fixed target
  - In-flight decay technique

NA62 Analysis Strategy

Signal and background regions are kept blind throughout the analysis

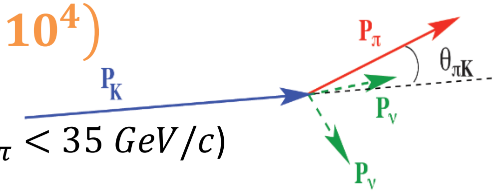
Decay backgrounds	
Decay mode	BR
$\mu^+\nu(\gamma)$	63.5%
$\pi^+\pi^0(\gamma)$	20.7%
$\pi^+\pi^+\pi^-$	5.6%
$\pi^+\pi^-e^+\nu$	4.2×10^{-5}
Other backgrounds	
Beam-gas interactions	
Upstream interactions	

Time resolution $\sim \mathcal{O}(100\ \text{ps})$

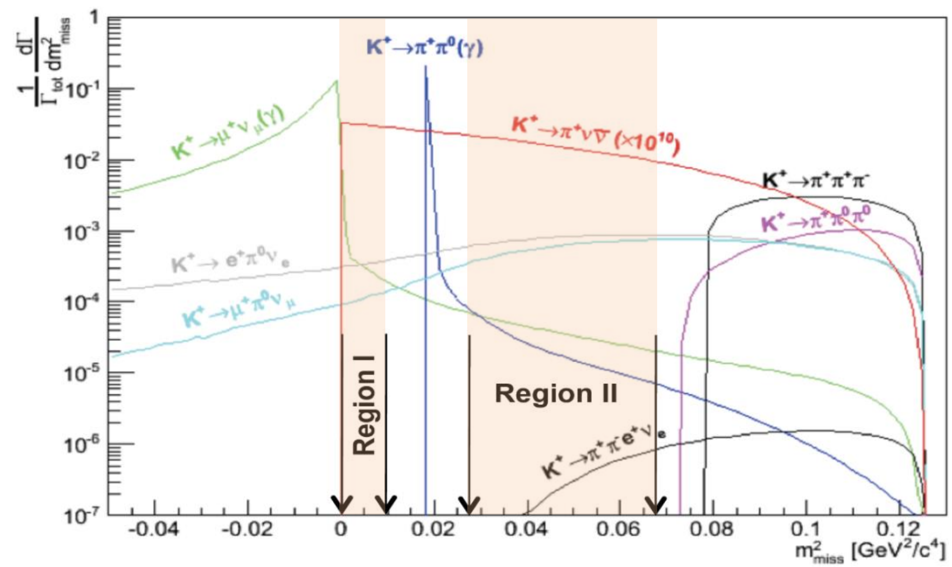
Matching of upstream-downstream activity

Kinematic suppression $\sim \mathcal{O}(10^4)$

- Kaon momentum
- π momentum ($15\ GeV/c < P_\pi < 35\ GeV/c$)



$$m^2_{miss} \cong m^2_K\left(1 - \frac{|P_\pi|}{|P_K|}\right) + m^2_\pi\left(1 - \frac{|P_K|}{|P_\pi|}\right) - |P_K||P_\pi|\theta^2_{\pi K}$$



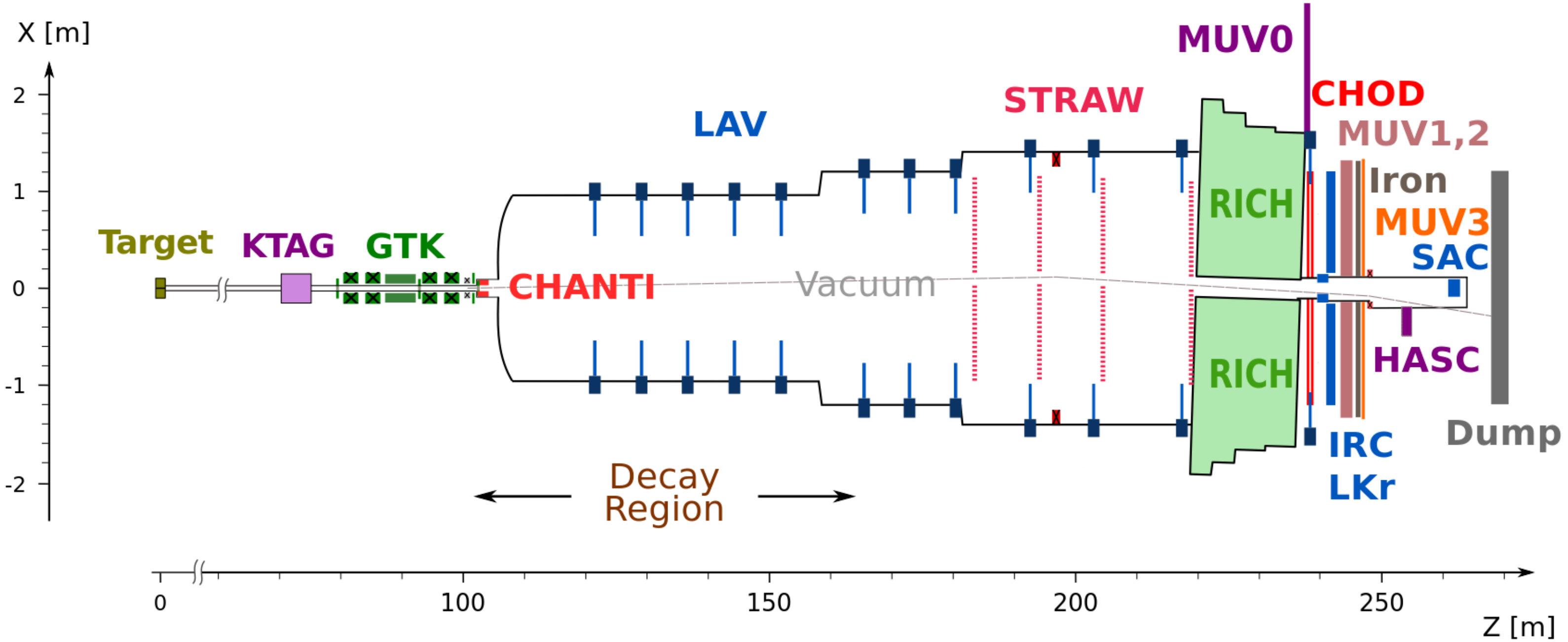
PID and high efficiency Veto systems

Muon suppression $> 10^7$

π^0 suppression $> 10^7$

- Particle ID (Cherenkov + calorimeters)
- Photon veto

NA62 Beam & Detector



❑ SPS Beam:

- 400 GeV/c protons
- 2×10^{12} protons/spill
- 3.5s spill

❑ Secondary positive beam

- 75 GeV/c momentum, 1% bite
- $100\ \mu$rad divergence (RMS)
- $60 \times 30\ \mathrm{mm}^2$ transverse size
- $K^+(6\%)/\pi^+(70\%)/p(24\%)$
- 33×10^{11} ppp on T10 (750 MHz at GTK3)

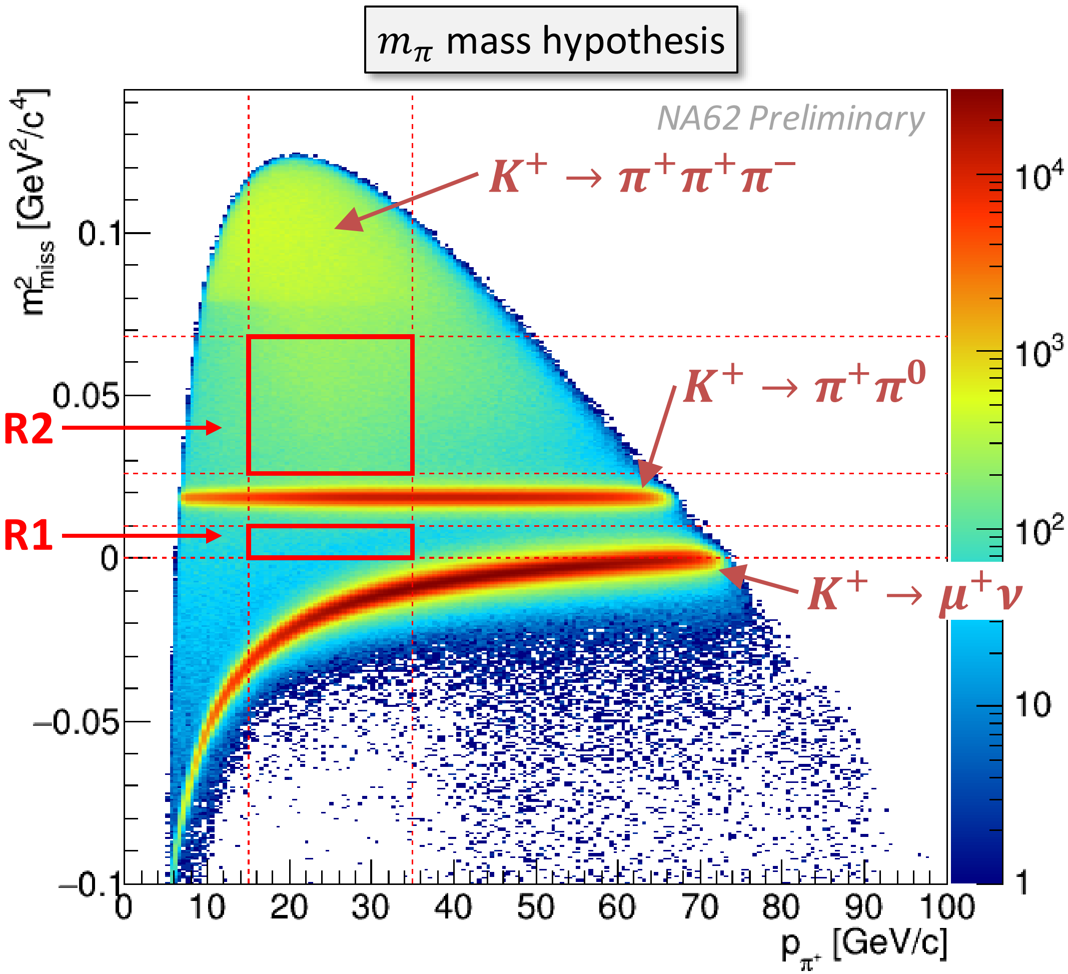
❑ Decay region

- 60 m long fiducial region
- ~ 5 MHz K^+ decay rate
- Vacuum $\sim\mathcal{O}(10^{-6})$ mbar

$K^+ \to \pi^+ \nu\bar{\nu}$ Signal Selection

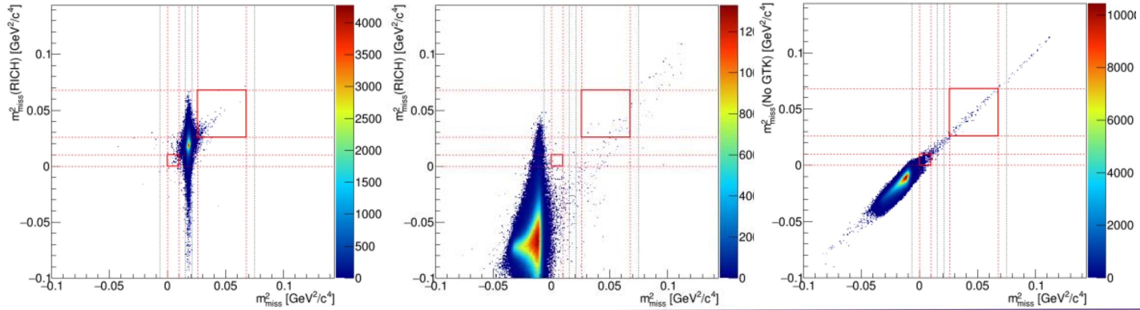
- **Selection criteria**
  - Single track topology
  - π^+ identification
  - Photon rejection
  - Multi-track rejection

- **Performances**
  - $\varepsilon_{\mu^+} = 1 \cdot 10^{-8}$ (64% π^+ efficiency)
  - $\varepsilon_{\pi^0} = 3 \times 10^{-8}$
  - $\sigma(\mathrm{m}^2_{\mathrm{miss}}) = 1 \times 10^{-3}\ \mathrm{GeV}^2/c^4$
  - $\sigma_t \sim \mathcal{O}(100\ \mathrm{ps})$



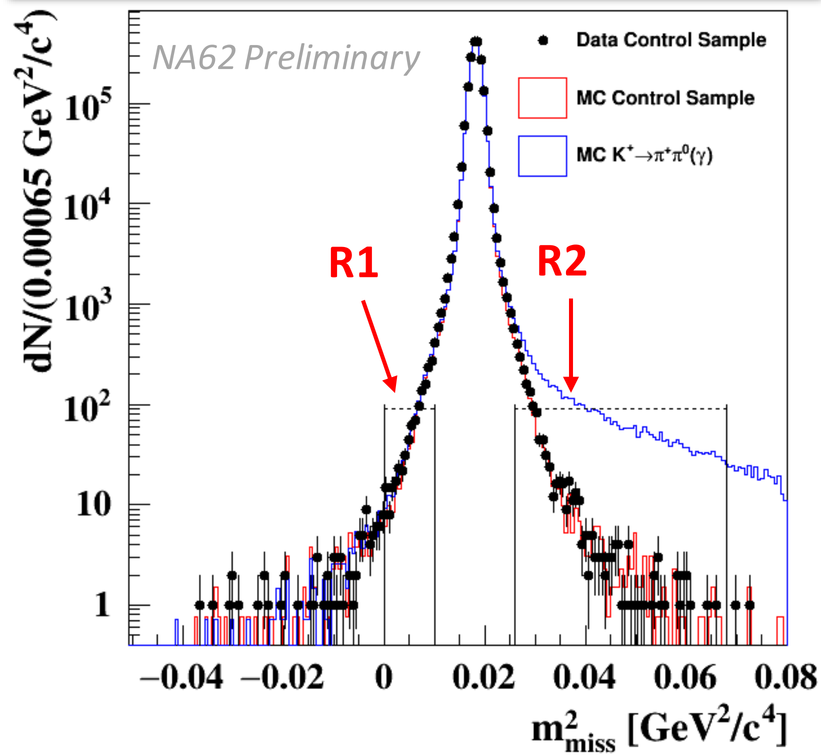
$K^+ \to \pi^+ \nu \bar{\nu}$ Signal Regions

- Three ways to compute $m^2_{miss} = (\mathbf{P_K} - \mathbf{P_\pi})^2$:
  - $m^2_{miss}(\text{GTK}, \text{Straw})$
  - $m^2_{miss}(\text{GTK}, \text{RICH})$
  - $m^2_{miss}(\text{Beam}, \text{Straw})$



- Protects against mis-reconstruction

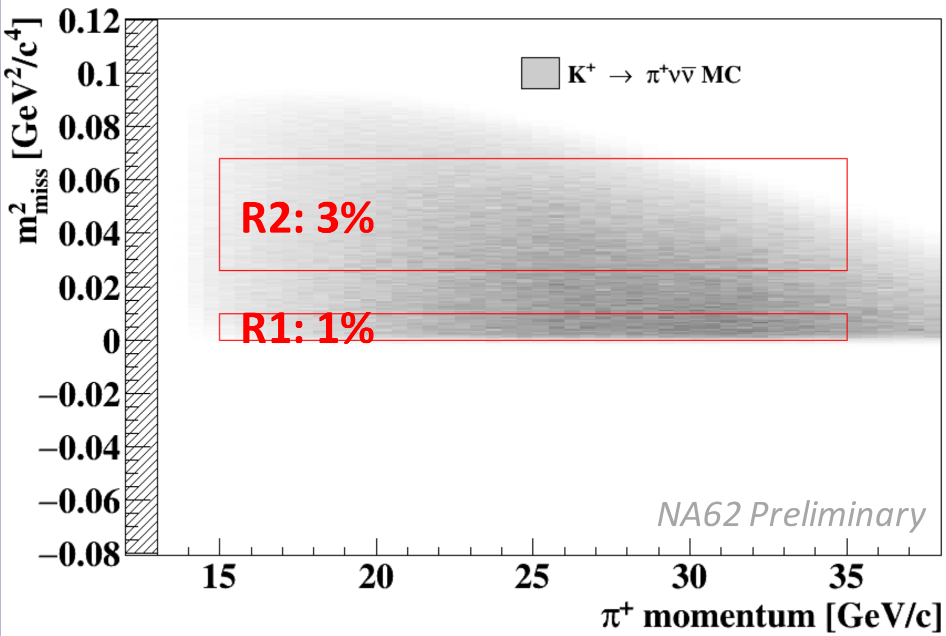
m^2_{miss} for $K^+ \to \pi^+\pi^0$ sample min. bias.



- Kinematic suppression
  - Measured on data samples selected using calorimeters
  - Fractions in signal regions:
    - $K^+ \to \pi^+\pi^0 \sim 1 \cdot 10^{-3}$ (resolution tails)
    - $K^+ \to \mu^+\nu_\mu \sim 3 \cdot 10^{-4}$

$K^+ \to \pi^+ \nu \bar{\nu}$ Single Event Sensitivity

- **Signal acceptance: 4%**
- **Normalization**
  - $K^+ \to \pi^+ \pi^0$ on control trigger
  - Acceptance: 10%
  - Number of kaon decays in the fiducial volume: $N_K = 1.21(2) \times 10^{11}$



- **Uncertainties**

Source	$\delta SES\ (10^{-10})$
Random Veto	± 0.17
N_K	± 0.05
Trigger efficiency	± 0.04
Definition of $\pi^+\pi^0$ region	± 0.10
Momentum spectrum	± 0.01
Simulation of π^+ interactions	± 0.09
Extra activity	± 0.02
GTK Pileup simulation	± 0.02
Total	± 0.24

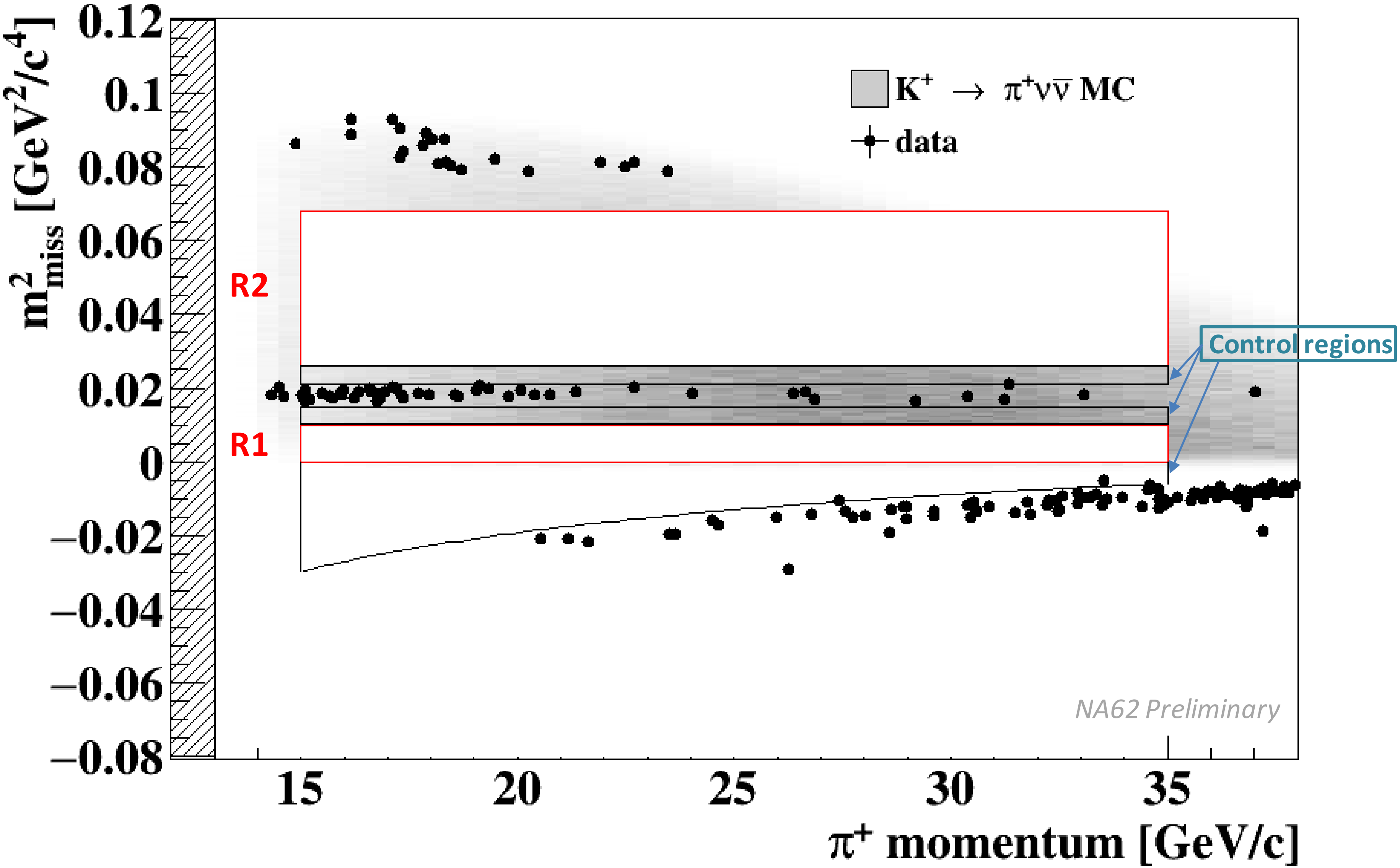
$$SES = (3.15 \pm 0.01_{stat} \pm 0.24_{syst}) \cdot 10^{-10}$$

$K^+ \to \pi^+ \nu\bar{\nu}$ Background Summary

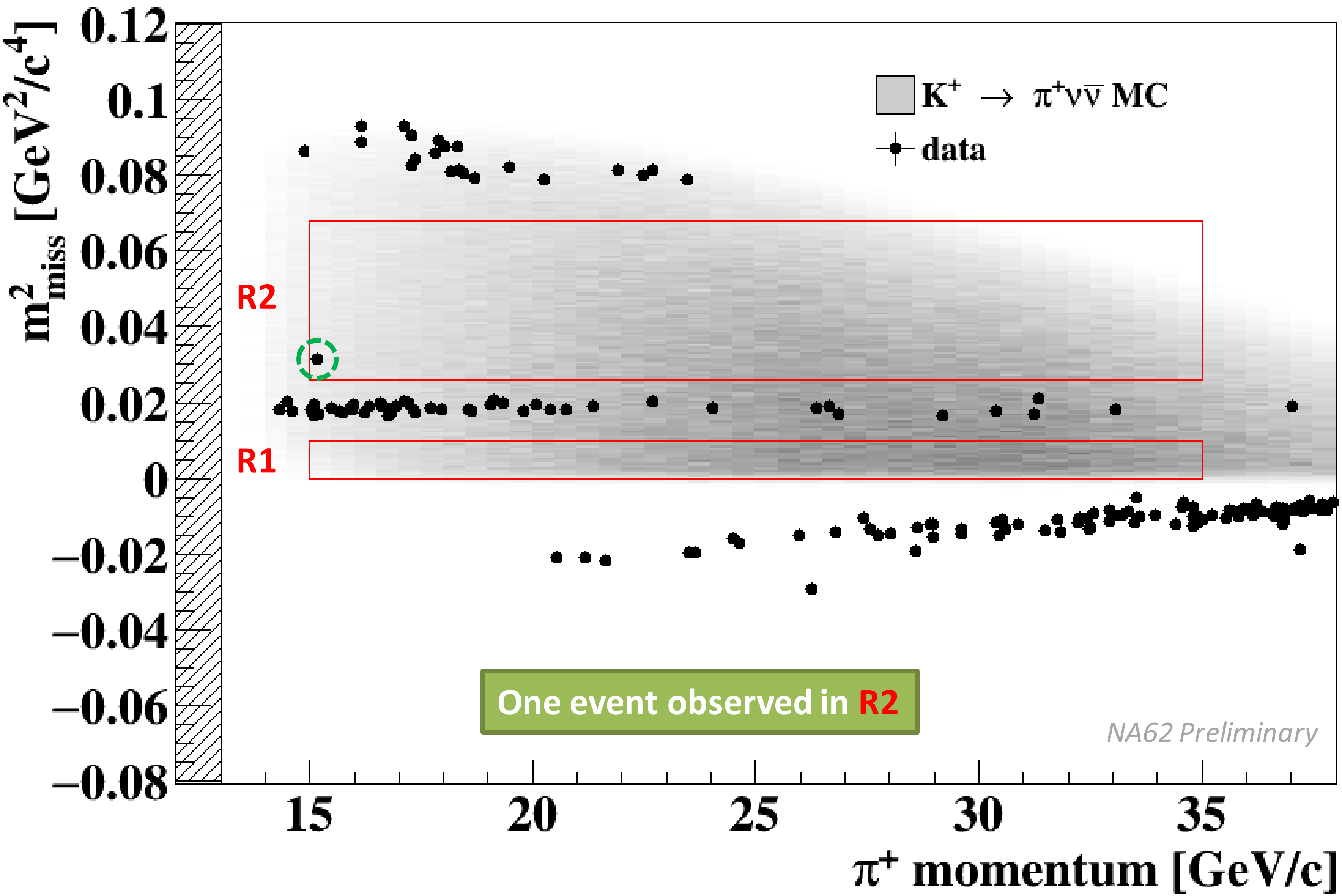
- $K^+ \to \pi^+ \pi^0 (\gamma)$
  - Data driven
  - Control region:
    1 observed (1.5 expected)
- $K^+ \to \mu^+ \nu_\mu (\gamma)$
  - Data driven
  - Control region:
    2 observed (1.1 expected)
- $K^+ \to \pi^+ \pi^- e^+ \nu_e$
  - Estimated with 400M MC decays
  - Good agreement across 5 validation samples
- **Upstream background (accidental and interactions)**
  - Data driven
  - Geometrical and Kaon-pion matching cuts effective

Process	Expected events (R1+R2)
$K^+ \to \pi^+ \nu\bar{\nu}$ (SM)	$0.267 \pm 0.001_{stat} \pm 0.020_{syst} \pm 0.032_{ext}$
Total Background	$0.15 \pm 0.09_{stat} \pm 0.01_{syst}$
$K^+ \to \pi^+ \pi^0 (\gamma)$ IB	$0.064 \pm 0.007_{stat} \pm 0.006_{syst}$
$K^+ \to \mu^+ \nu (\gamma)$ IB	$0.020 \pm 0.003_{stat} \pm 0.003_{syst}$
$K^+ \to \pi^+ \pi^- e^+ \nu$	$0.018^{+0.024}_{-0.017}\Big\vert_{stat} \pm 0.009_{syst}$
$K^+ \to \pi^+ \pi^+ \pi^-$	$0.002 \pm 0.001_{stat} \pm 0.002_{syst}$
Upstream Bckg	$0.050^{+0.090}_{-0.030}\Big\vert_{stat}$

$K^+ \to \pi^+\nu\bar{\nu}$ Results



$K^+ \to \pi^+ \nu\bar{\nu}$ Results



$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ Results

- One event observed in Region 2
- Full exploitation of the CLs method in progress
- The results are compatible with the Standard Model
  - $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) < 11 \times 10^{-10}$ @ 90% CL
  - $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% CL

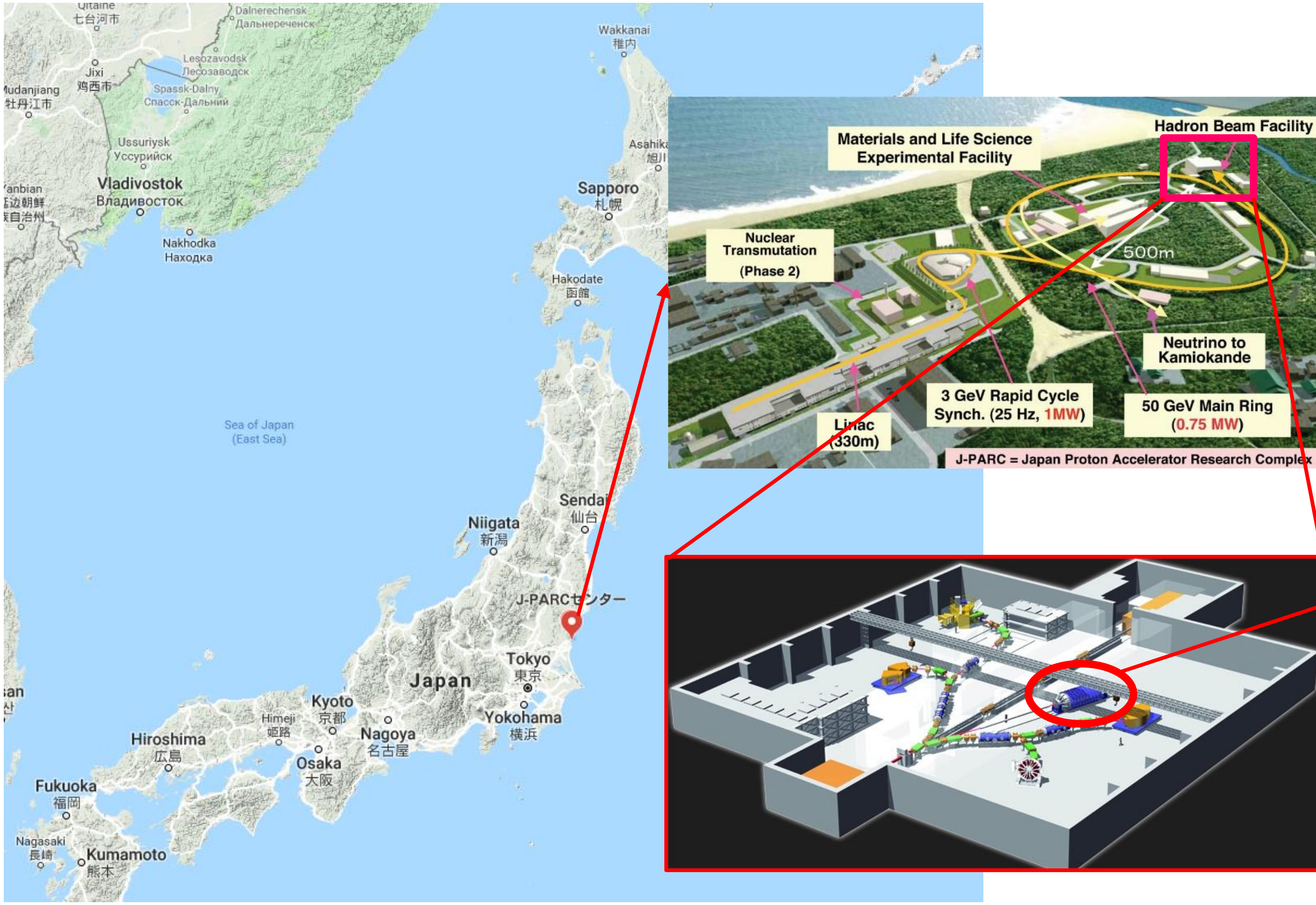
- For comparison
  - $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu}) = 28^{+44}_{-23} \times 10^{-11}$ @ 68% CL
  - $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{SM} = (8.4 \pm 1.0) \times 10^{-11}$
  - $BR(K^+ \rightarrow \pi^+ \nu\bar{\nu})_{exp} = \left(17.3^{+11.5}_{-10.5}\right) \times 10^{-11}$ (BNL)

$K^+ \rightarrow \pi^+ \nu\bar{\nu}$ NA62 prospects

- **Analysis of data collected in 2017 started**
  - 20 times more data than the presented statistics
  - Expect improvements on signal acceptance, background reduction and reconstruction efficiency
- **2018 Data taking ongoing (April – November 2018)**
- **Expect ~ 20 SM events before LS2**
- **Data taking after 2018 to be approved**

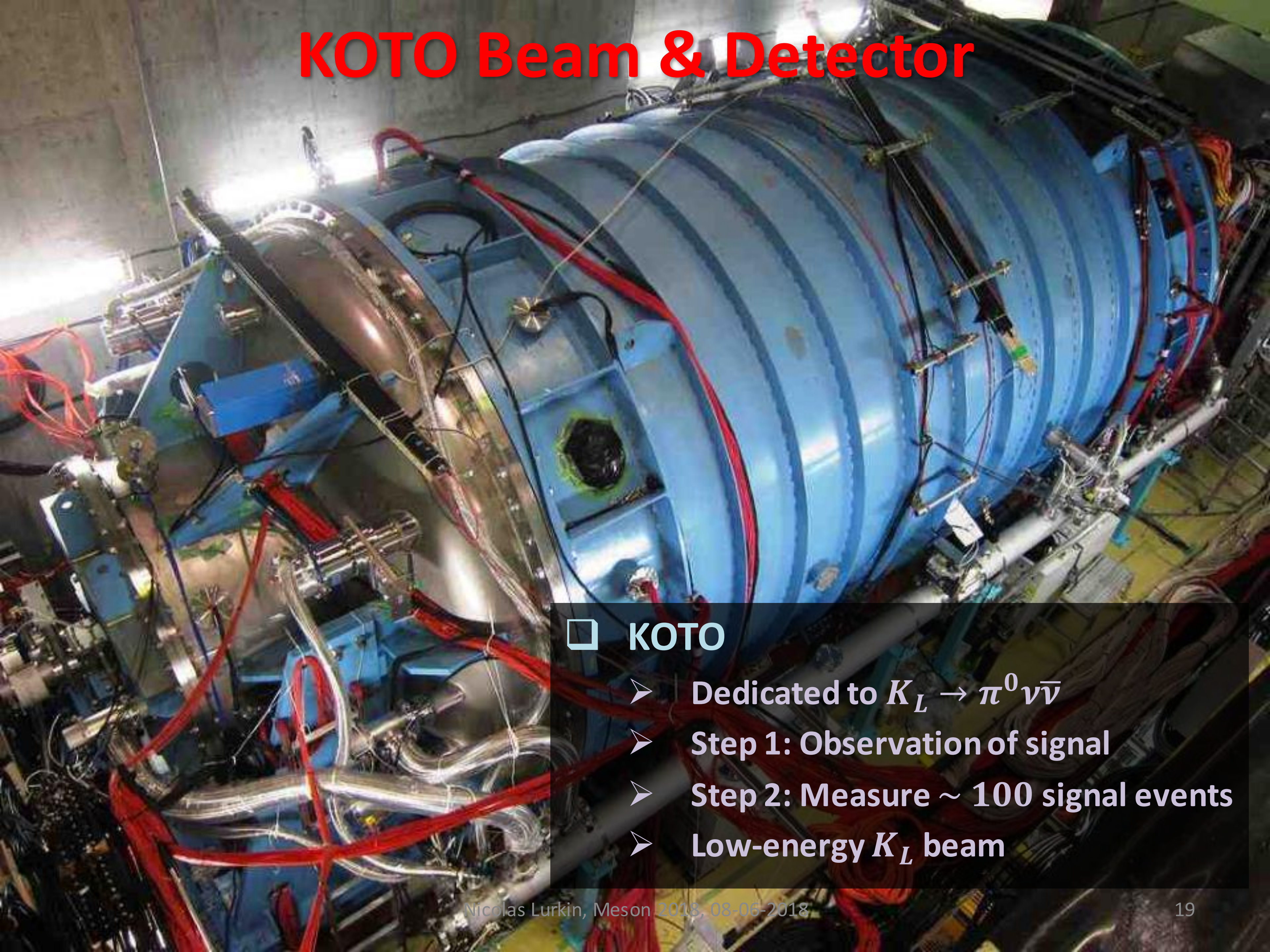
The KOTO Experiment

Study of $K_L \to \pi^0 \nu \bar{\nu}$ @ J-PARC



Arizona, Chicago, Chonbuk, Hanyang, Jeju, JINR, KEK, Kyoto, Michigan, NDA, NTU, Okayama, Osaka, Pusan, Saga, Yamagata

KOTO Beam & Detector

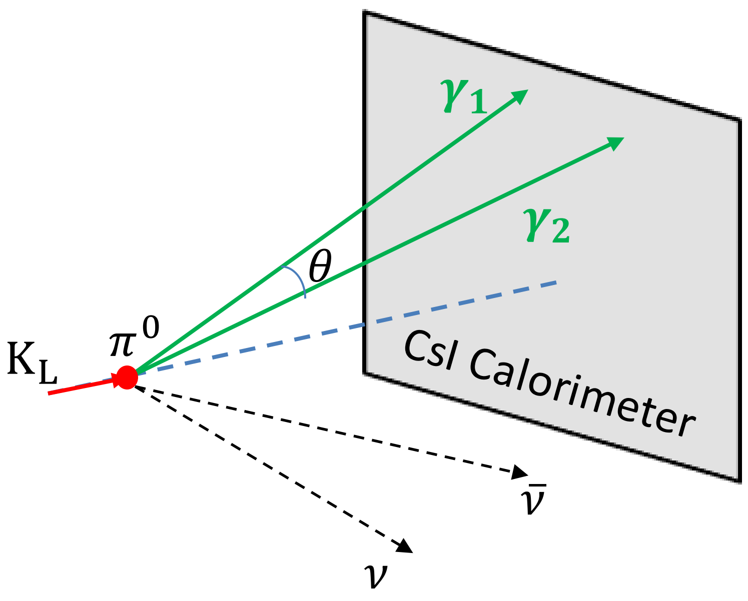


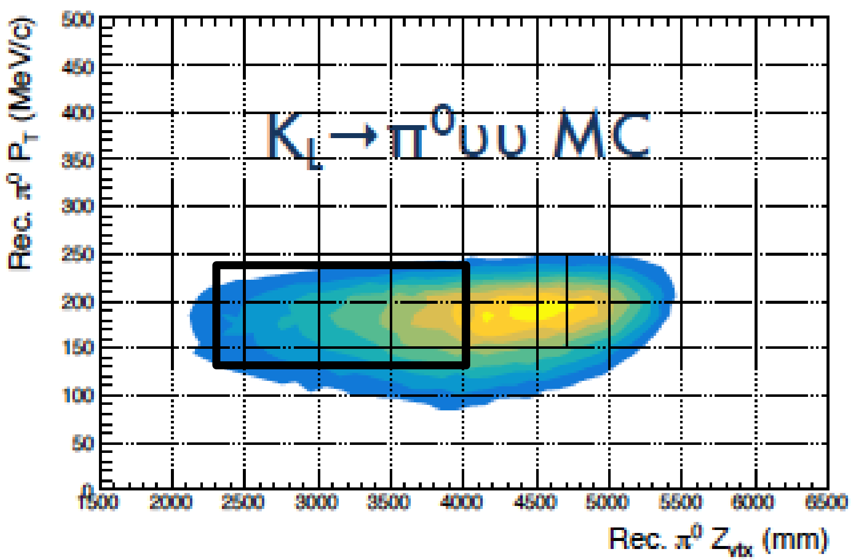
- **KOTO**
  - Dedicated to $K_L \to \pi^0 \nu \bar{\nu}$
  - Step 1: Observation of signal
  - Step 2: Measure ~ 100 signal events
  - Low-energy K_L beam

KOTO Analysis Strategy

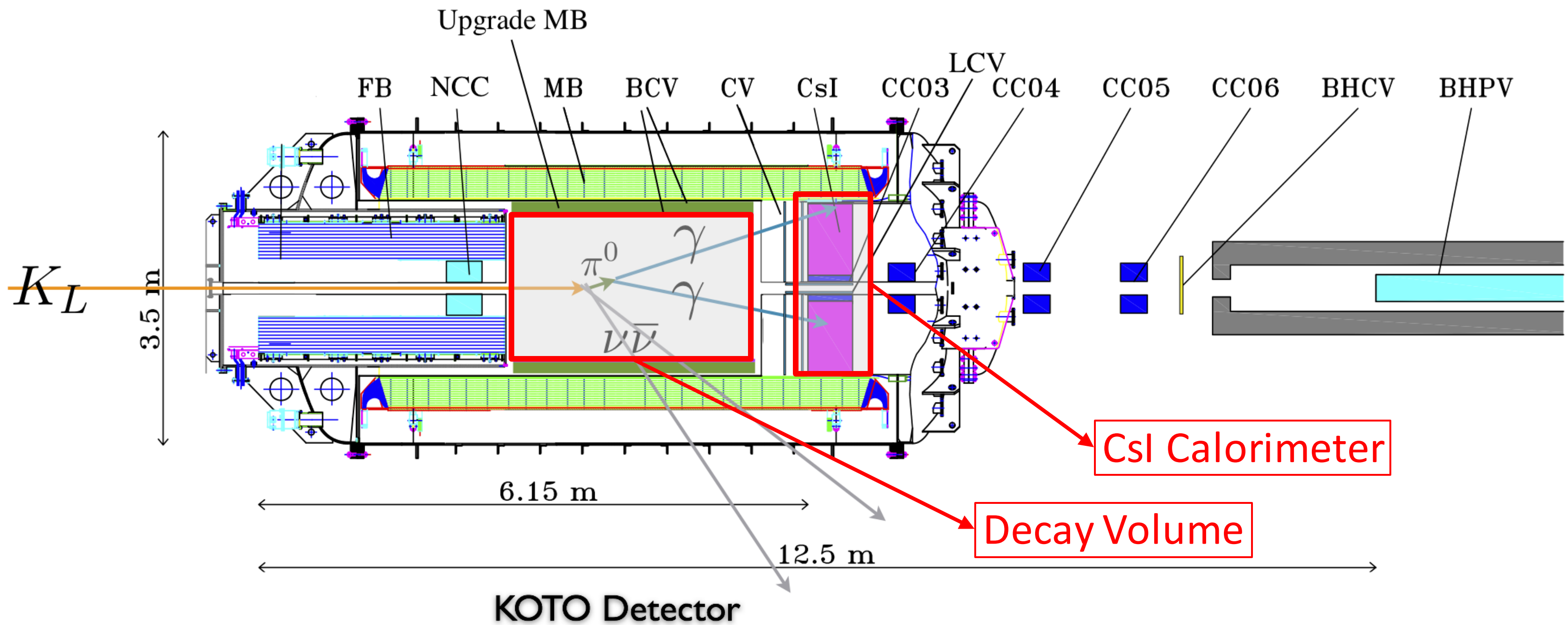
- **Signal signature:**
  - 2 photons + Missing P_t
- **Assuming 2γ from π^0**
  - $M^2_{\pi^0} = (E_{\gamma 1} + E_{\gamma 2})^2 - (\vec{P}_{\gamma 1} + \vec{P}_{\gamma 2})^2 = 2E_{\gamma 1}E_{\gamma 2}(1 - \cos\theta)$
  - $\cos\theta = 1 - \frac{M^2_{\pi^0}}{2E_{\gamma 1}E_{\gamma 2}}$
- **Signal region defined by reconstructed π^0 transverse momentum P_t and Z_{vtx}**

- **Background rejection**
  - Hermetic Veto Detector
- **Photon energy measurement**
  - Cesium Iodide Calorimeter (CsI)



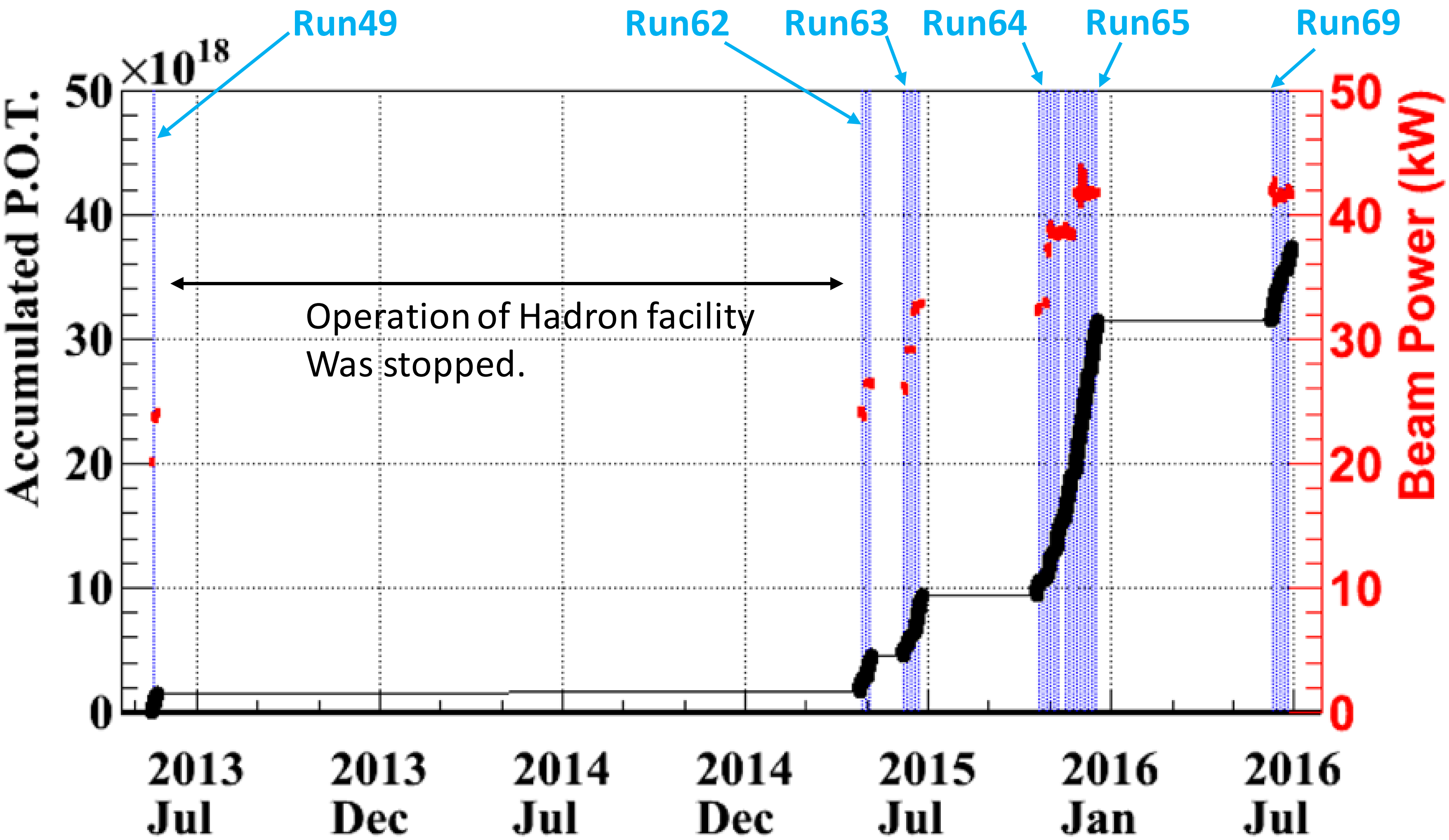


KOTO Beam & Detector



- **Beam:**
  - Primary 30 GeV/c proton beam
  - Secondary beam on gold target at 16°
  - K_L peak energy at 1.4 GeV/c
  - Intensity: 25 kW (2013), 30/42 kW (2015/2016)
- **Decay region:**
  - 3 m long fiducial region
  - Vacuum: 5×10^{-7} mbar

KOTO Runs

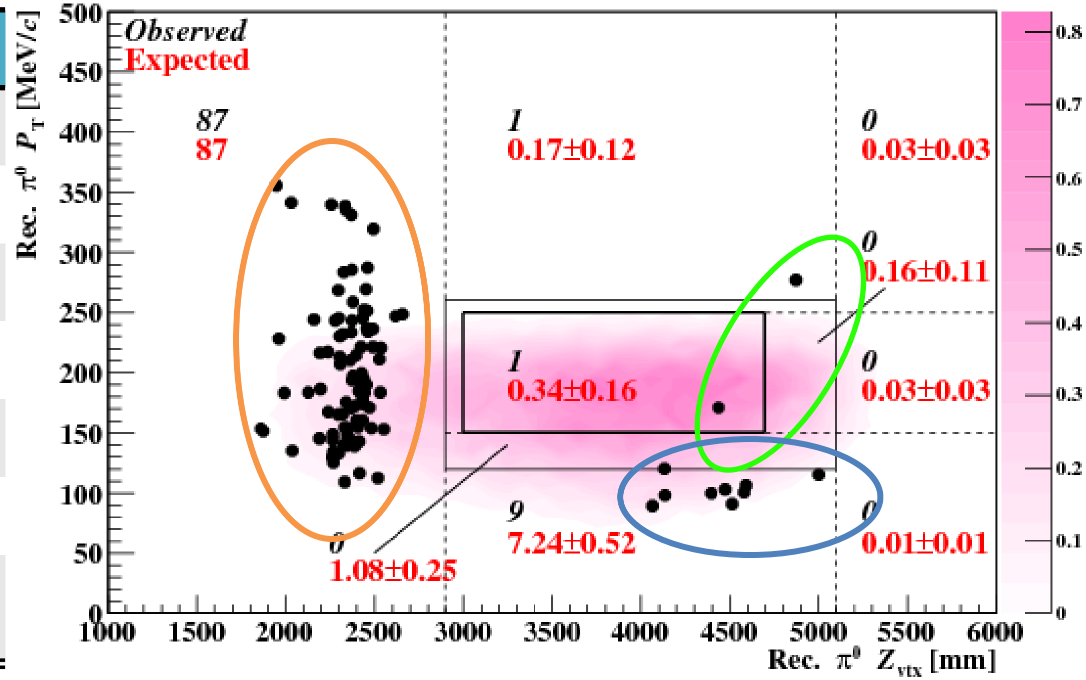


Run49
Run62
Run63
Run64
Run65
Run69
×10^18
Accumulated P.O.T.
Beam Power (kW)
50
40
30
20
10
0
Operation of Hadron facility
Was stopped.
2013 Jul
2013 Dec
2014 Jul
2014 Dec
2015 Jul
2016 Jan
2016 Jul

KOTO 2013 Result

- Data from ~100 hours run
  - $N(K_L) \sim 2.4 \times 10^{11}$ (SES 1.3×10^{-8})
- Upper limit
  - $BR(K_L \to \pi^0 \nu\bar{\nu}) < 5.1 \times 10^{-8}$ (90% C.L.) [PTEP 2017, 021C01]

Background source	# of events
$K_L \to 2\pi^0$	0.047 ± 0.033
$K_L \to \pi^+\pi^-\pi^0$	0.002 ± 0.002
$K_L \to 2\gamma$	0.030 ± 0.018
Pileup of accidental hits	0.014 ± 0.014
Other K_L background	0.010 ± 0.005
Halo neutrons hitting NCC	0.056 ± 0.056
Halo neutrons hitting the calorimeter	0.18 ± 0.15
Total	0.34 ± 0.16



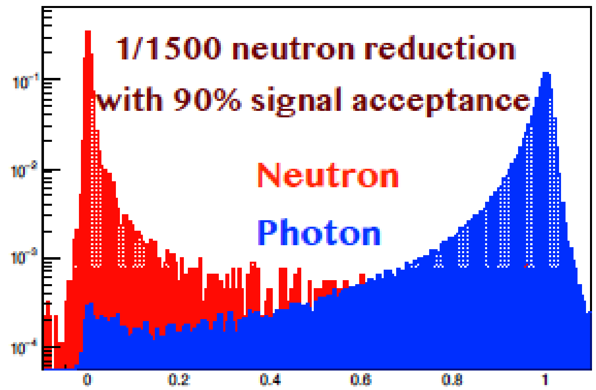
KOTO After 2013

- ❑ **Specific runs using Al target to collect and study neutron induced events**
  - ➢ Neural Network trained to discriminate photon – neutron clusters in CsI
  - ➢ Pulse shape analysis
  - ➢ × 5 reduction of neutron background

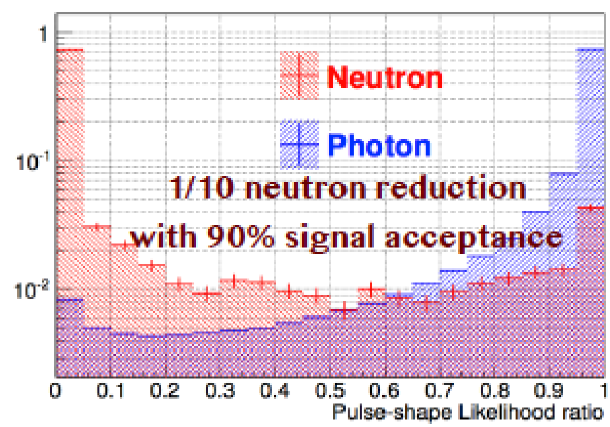
- ❑ **Beam profile monitor**
  - ➢ Better alignment
- ❑ **Thinner vacuum window**
  - ➢ 125 μm → 12.5 μm
  - ➢ Reduce neutron interaction

- ❑ **New Beam Pipe Charged Veto**
  - ➢ Wire chamber instead of plastic scintillator
  - ➢ 99% efficient
  - ➢ Acceptance loss reduced by ~ 40%

- **Cluster Shape Discrimination**



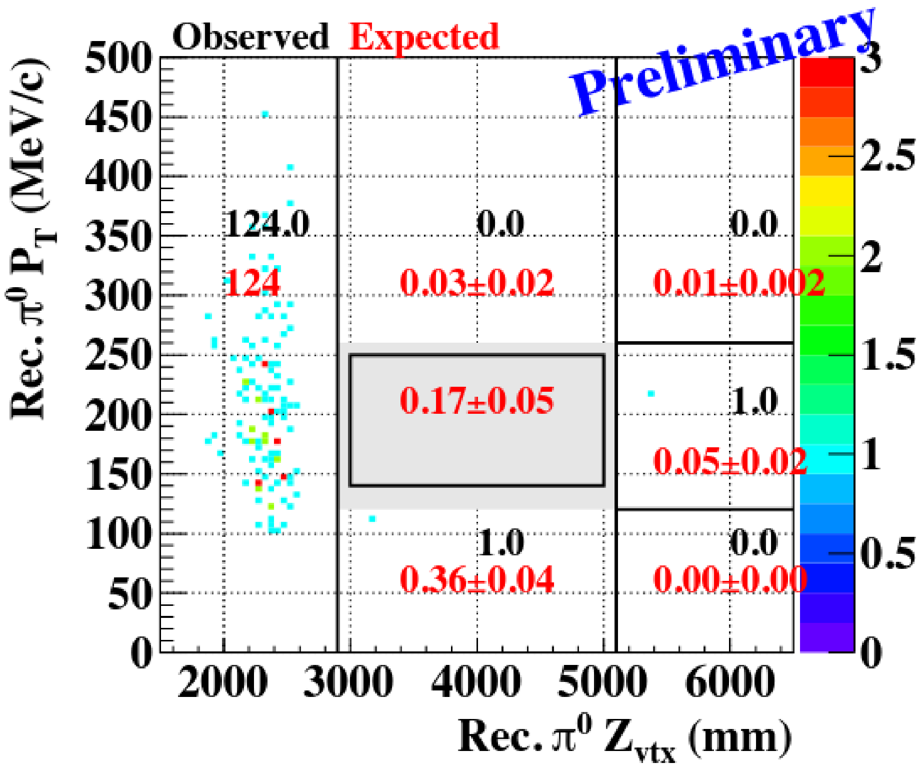
- **Pulse Shape Discrimination**



KOTO 2015 Analysis

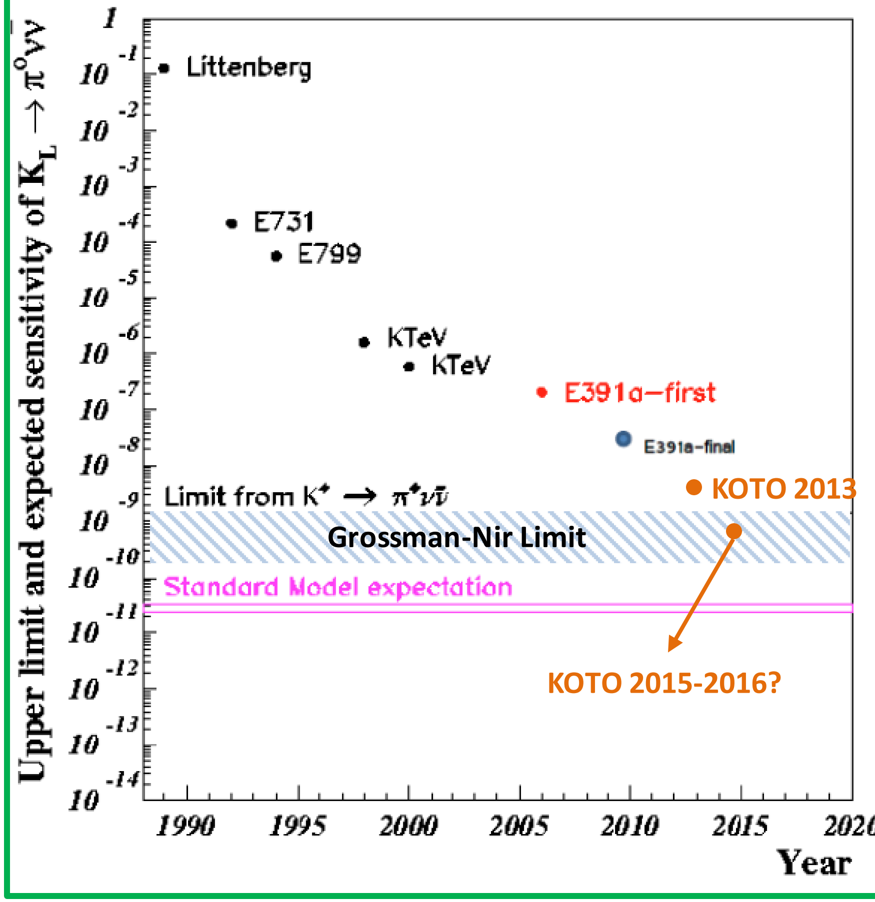
- Based on a small subsample of 2015 – 2016 statistics
  - ~ 60% more statistics than 2013
  - Wider signal region thanks to better background rejection: +40% signal acceptance
  - SES ~ 5.9×10^{-9}

Background source	# of events
$K_L \to 2\pi^0$	0.04 ± 0.03
$K_L \to \pi^+\pi^-\pi^0$	0.04 ± 0.01
Halo neutrons hitting NCC (upstream)	0.04 ± 0.04
Halo neutrons hitting CsI	0.05 ± 0.02
Total	0.17 ± 0.05

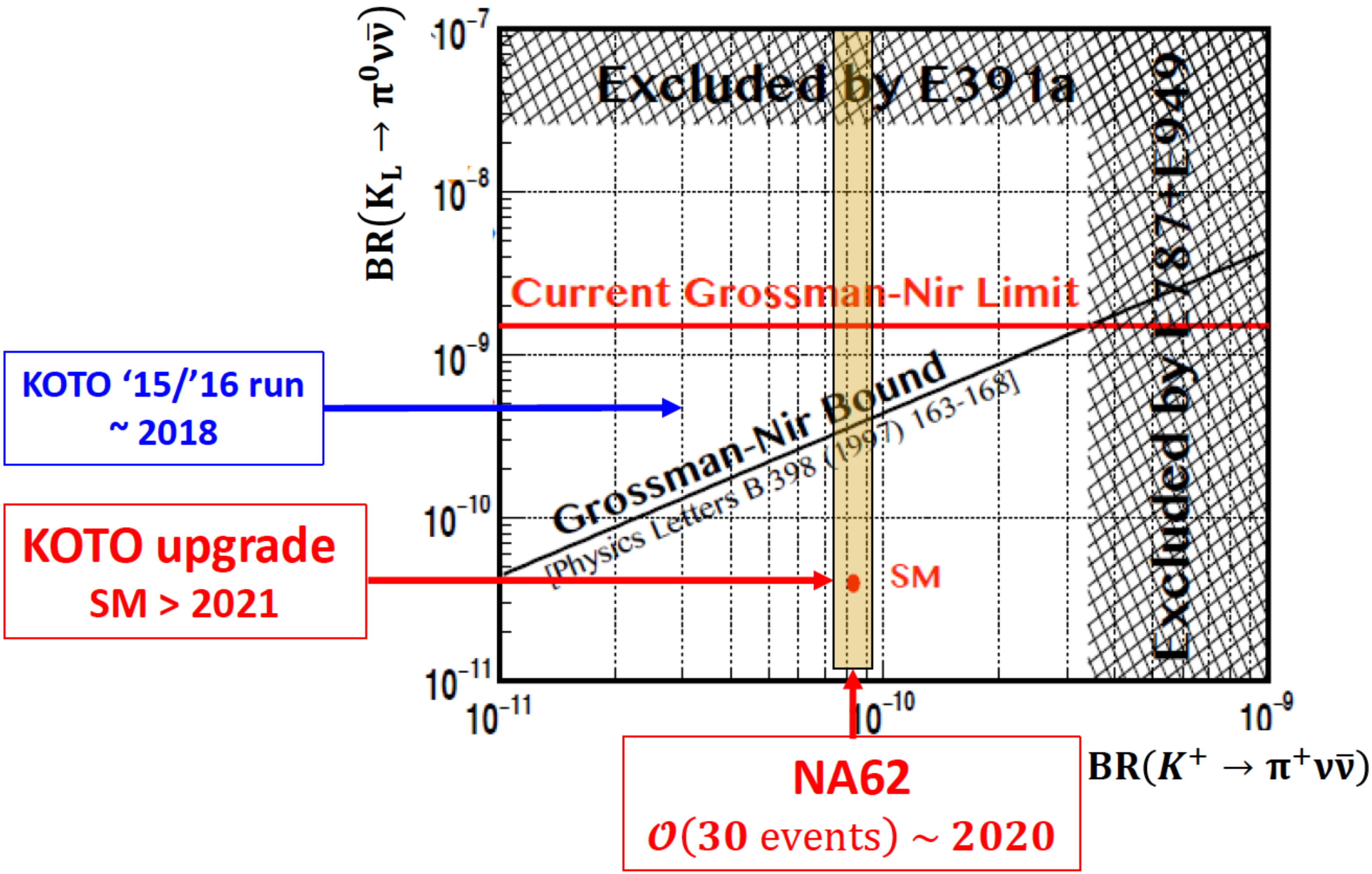


KOTO Prospects

- ❑ **Full 2015 – 2016 analysis:**
  - ➢ $< 10^{-9}$ SES
- ❑ **Upgrades needed to reach SM**
  - ➢ New barrel detector (April 2016)
  - ➢ Beam pipe modification (ongoing)
  - ➢ CsI both end readout (2018)
  - ➢ J-PARC 42 kW → 100 kW (2019)



$K \to \pi\nu\bar{\nu}$ Prospects



Conclusions

- **The novel NA62 decay-in-flight technique works**
- **SM sensitivity for $K^+ \to \pi^+ \nu\bar{\nu}$ reached with the completion of 2016 analysis**
- **One event observed in 2016 data (expect 0.3 SM in R1+R2)**
  - $BR(K^+ \to \pi^+ \nu\bar{\nu}) < 14 \times 10^{-10}$ @ 95% C. L.

- **Kaon experiment NA62 at CERN and KOTO at J-PARC are exploring physics beyond SM primarily via $K \to \pi\nu\bar{\nu}$ for $10 - 10^3$ TeV scale:**
  - $K^+ \to \pi^+ \nu\bar{\nu}$: NA62 measurement expected in the next few years
  - $K_L \to \pi^0 \nu\bar{\nu}$: KOTO expected to reach $< 10^{-9}$ sensitivity soon; SM sensitivity expected by 2021
- **Both experiment are running and data analysis on-going**

Spares

On behalf of the NA62 collaboration

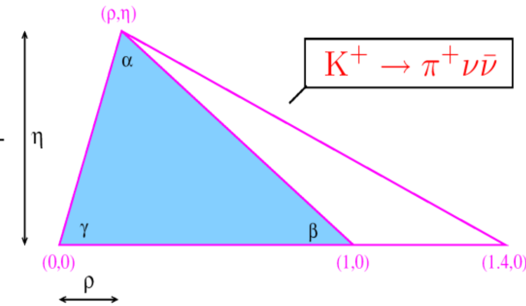
Nicolas Lurkin
School of Physics and Astronomy, University of Birmingham
Meson 2018, 08-06-2018

CKM Triangle

- K physics alone can fully constrain the CKM unitarity triangle

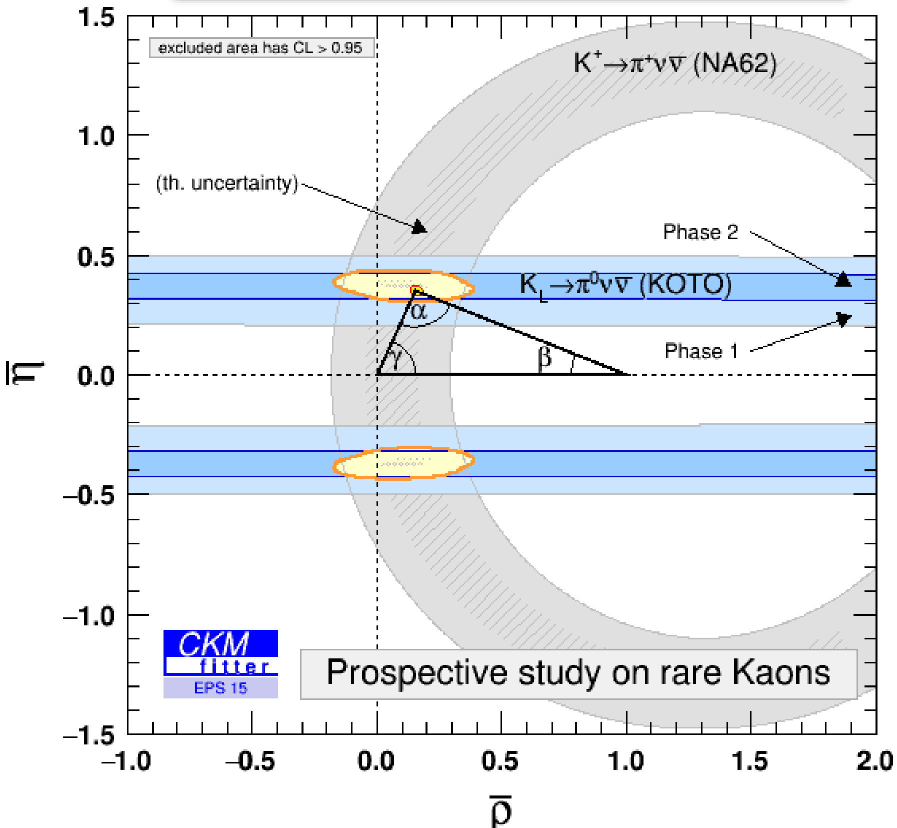
$K_L \to \pi^0 \nu \bar{\nu}$

$K_L \to \pi^0 e^+ e^- \left\{ \begin{array}{l} K_S \to \pi^0 e^+ e^- \\ K_L \to \pi^0 \gamma\gamma \\ K_L \to e e \gamma\gamma \end{array} \right.$



$K_L \to \mu^+ \mu^- \left\{ \begin{array}{l} K_L \to \gamma\gamma,\ K_L \to e^+ e^- \gamma \\ K_L \to e^+ e^- e^+ e^-,\ e^+ e^- \mu^+ \mu^- \end{array} \right.$

CKM unitarity triangle with kaons

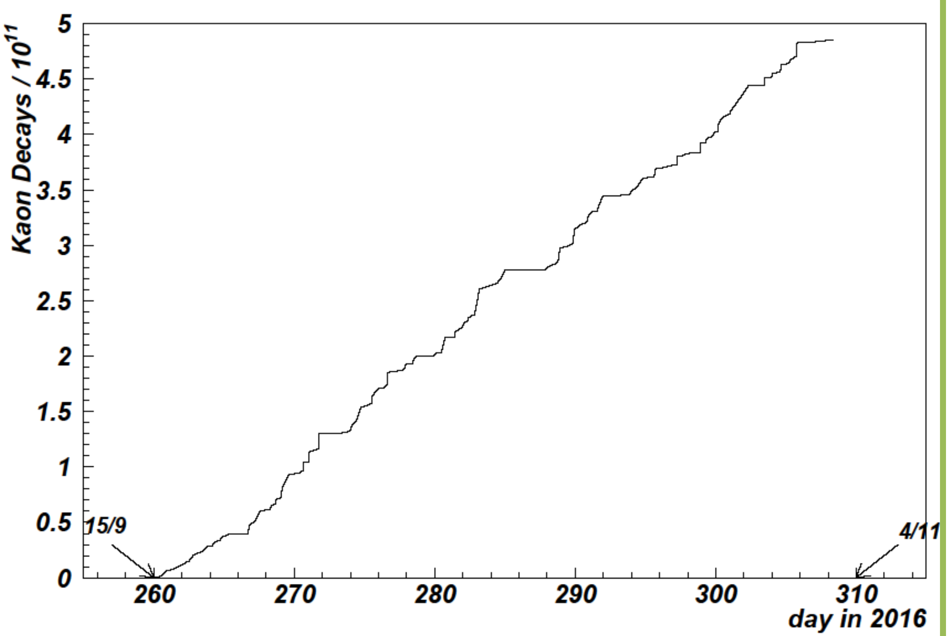


- Comparison with B physics can provide description of NP flavour dynamics

NA62 "Luminosity"

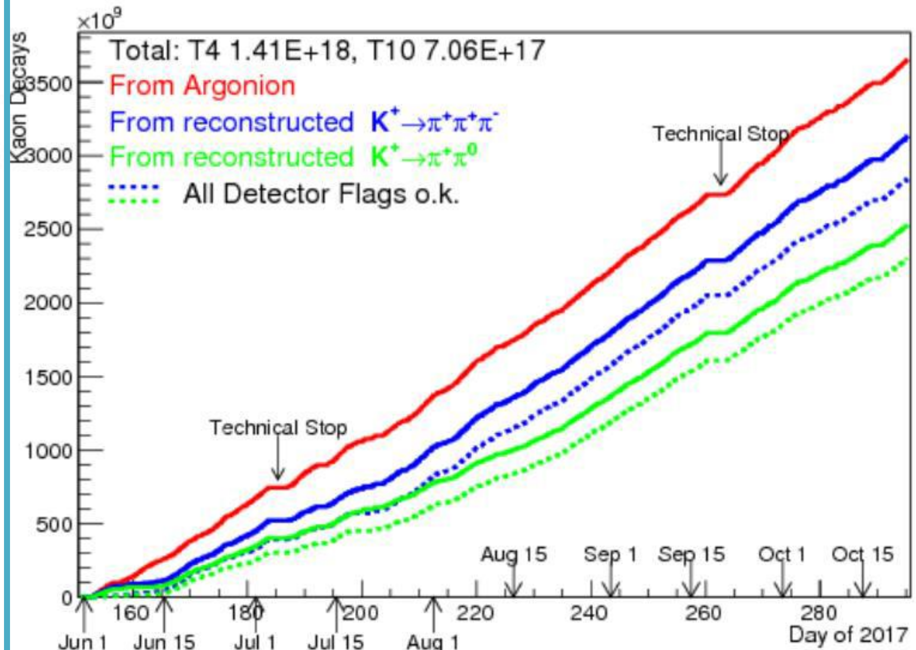
2016 run

- 13×10^{11} ppp on target (40% nominal)
- $\sim 1 \times 10^{11}$ K^+ decays useful for $\pi\nu\nu$



2017 run

- 20×10^{11} ppp on target (60% nominal)
- $> 3 \times 10^{12}$ K^+ decays collected



Single Event Sensitivity

$A_{\pi\nu\bar{\nu}} = 0.04 \pm 0.001$
Signal acceptance

$\varepsilon_{RV} = 0.76 \pm 0.04$
Random veto

$$\boldsymbol{SES} = \frac{\mathbf{1}}{\mathrm{N_K} \times A_{\pi\nu\bar{\nu}} \times \varepsilon_{\mathrm{trig}} \times \varepsilon_{RV}}$$

$\varepsilon_{\mathrm{trig}} = 0.87 \pm 0.02$
Trigger efficiency

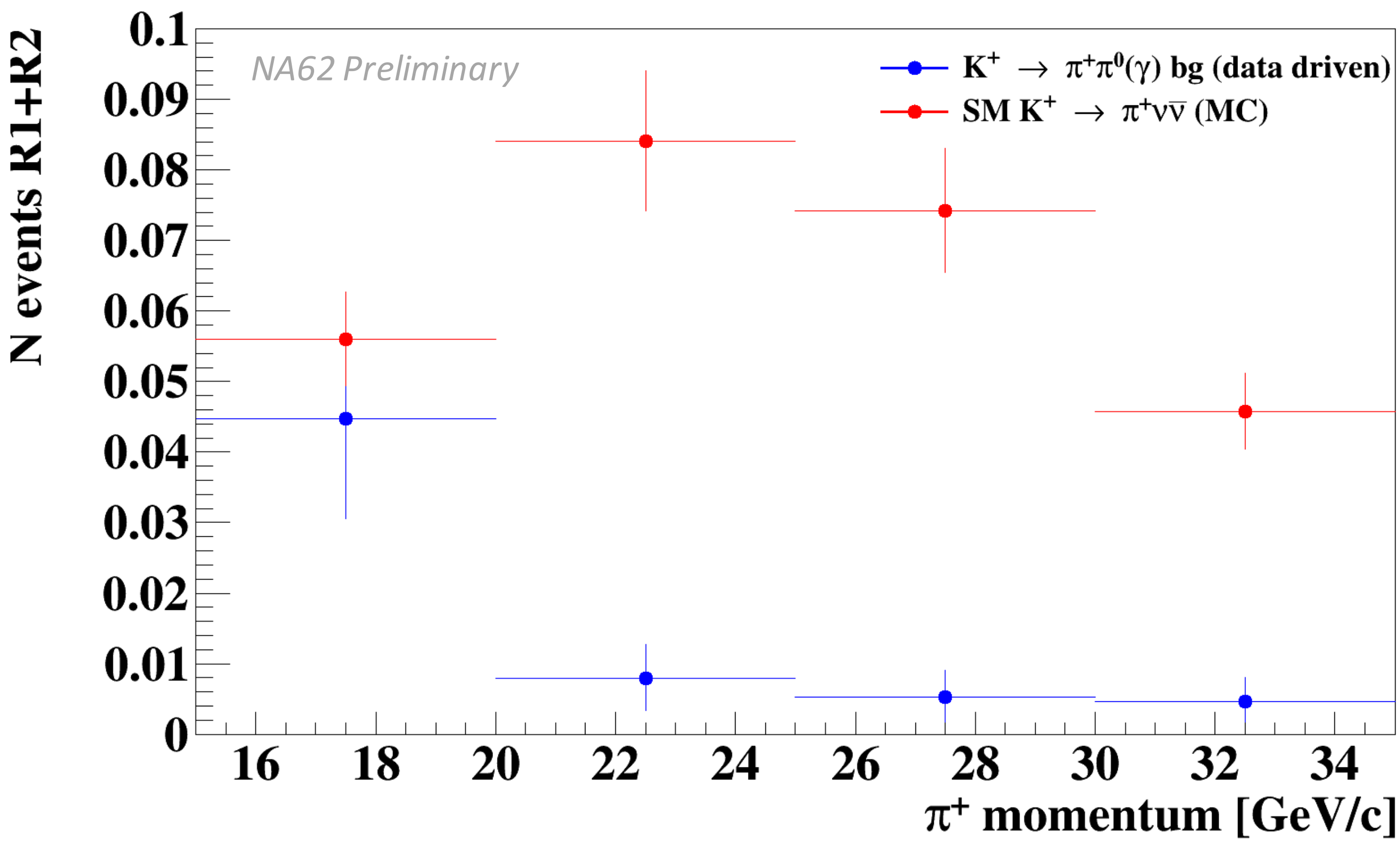
$N_K = (1.21 \pm 0.02) \times 10^{11}$
Kaon decays

Source	$\delta SES\ (10^{-10})$
Random Veto	± 0.17
N_K	± 0.05
Trigger efficiency	± 0.04
Definition of $\pi^+\pi^0$ region	± 0.10
Momentum spectrum	± 0.01
Simulation of π^+ interactions	± 0.09
Extra activity	± 0.02
GTK Pileup simulation	± 0.02
Total	± 0.24

$$\mathbf{SES} = \left(\mathbf{3.15 \pm 0.01_{stat} \pm 0.24_{syst}}\right) \times \mathbf{10^{-10}}$$

$K^+ \to \pi^+\pi^0(\gamma)$ Background

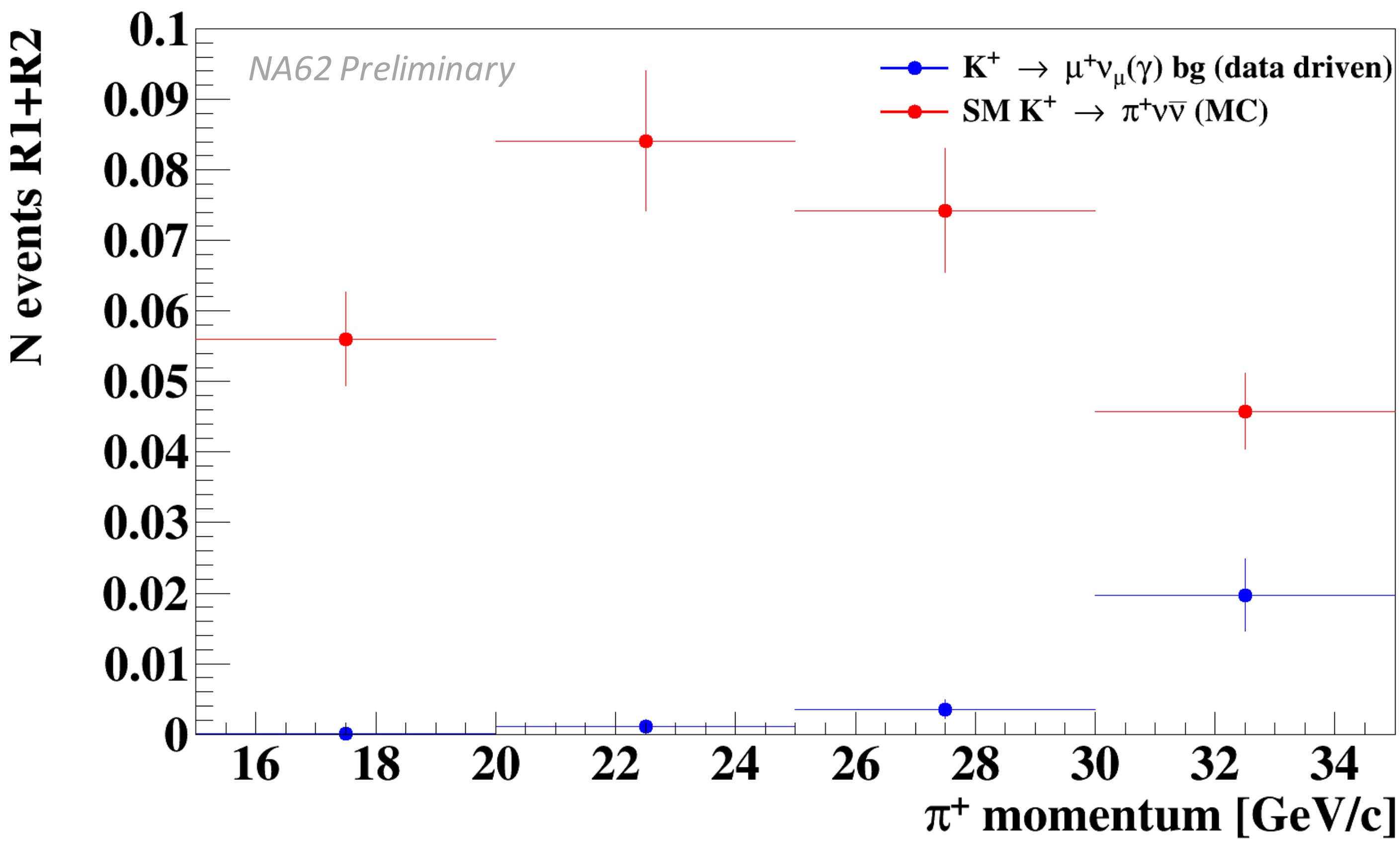
- Data driven background estimation
- Control region validation: 1 event observed (1.5 expected)



$$N^{bg}_{\pi\pi(\gamma)} = 0.064 \pm 0.007_{stat} \pm 0.006_{syst}$$

$K^+ \to \mu^+\nu_\mu(\gamma)$ Background

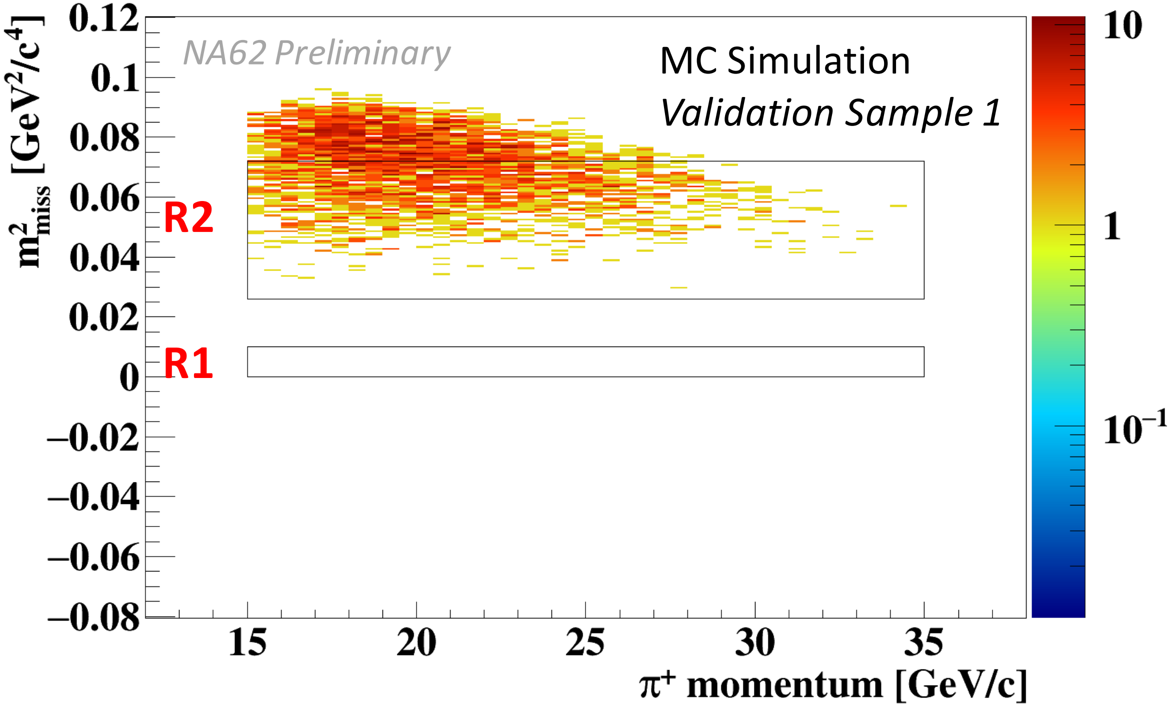
- Data driven background estimation
- Control region validation: 2 event observed (1.1 expected)



$$N^{bg}_{\mu\nu(\gamma)} = 0.020 \pm 0.003_{stat} \pm 0.003_{syst}$$

$K^+ \rightarrow \pi^+\pi^+e^-\nu_e$ Background

- Background estimated with 400M MC generated $K^+ \rightarrow \pi^+\pi^-e^+\nu_e$ decays
- Good agreement across the 5 validation samples



Validation sample	N expected	N observed
1	15.5(4)	8
2	4.0 (4)	2
3	3.2 (2)	3
4	0.7 (1)	1
5	1.2 (1)	5

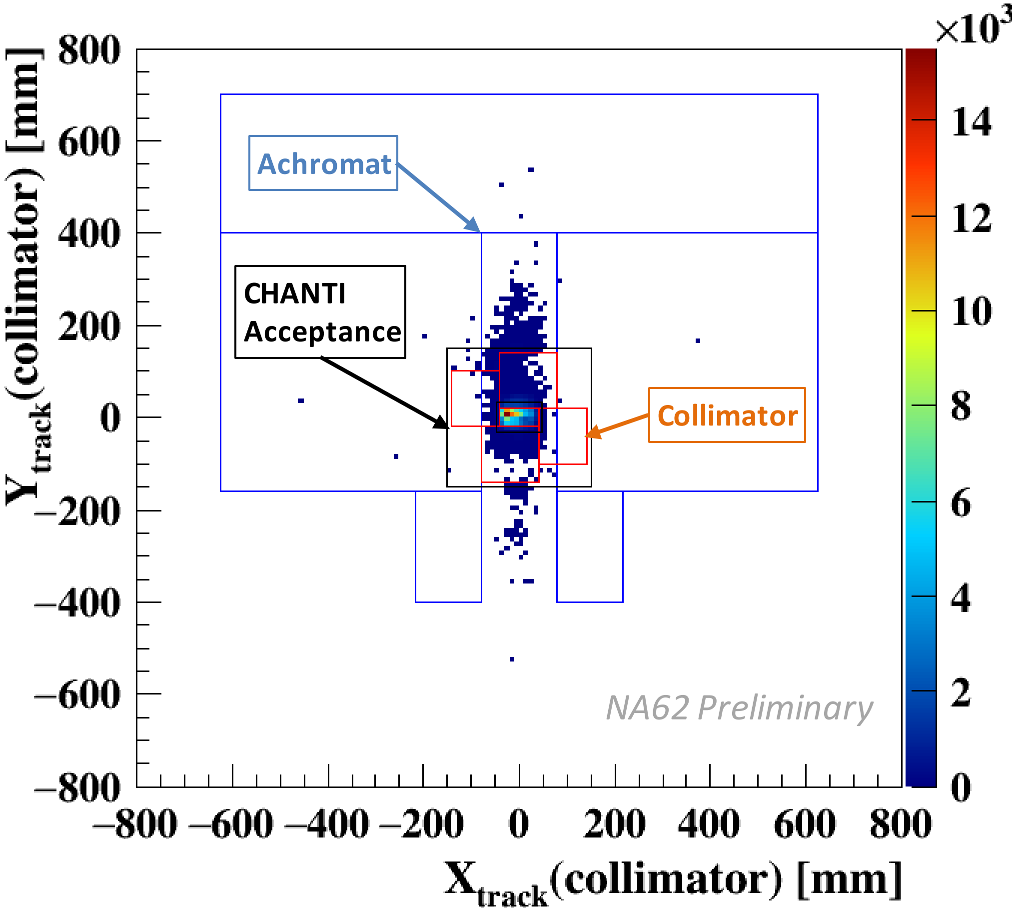
$$N^{bg}_{\pi^+\pi^-e^+\nu_e} = 0.018^{+0.024}_{-0.017}\Big|_{stat} \pm 0.009_{syst}$$

Upstream Background

- Data driven background estimation

- Accidental particles from the beam line
- Pions from interactions with beam spectrometer material

$\Longrightarrow$ **Kaon-pion matching and geometrical cuts effective**



$$N^{\mathrm{bg}}_{\mathrm{upstream}} = 0.050^{+0.090}_{-0.030}$$

$K^+ \to \pi^+ \nu \bar{\nu}$ Candidate

- The $K^+ \to \pi^+ \nu \bar{\nu}$ candidate event in the RICH